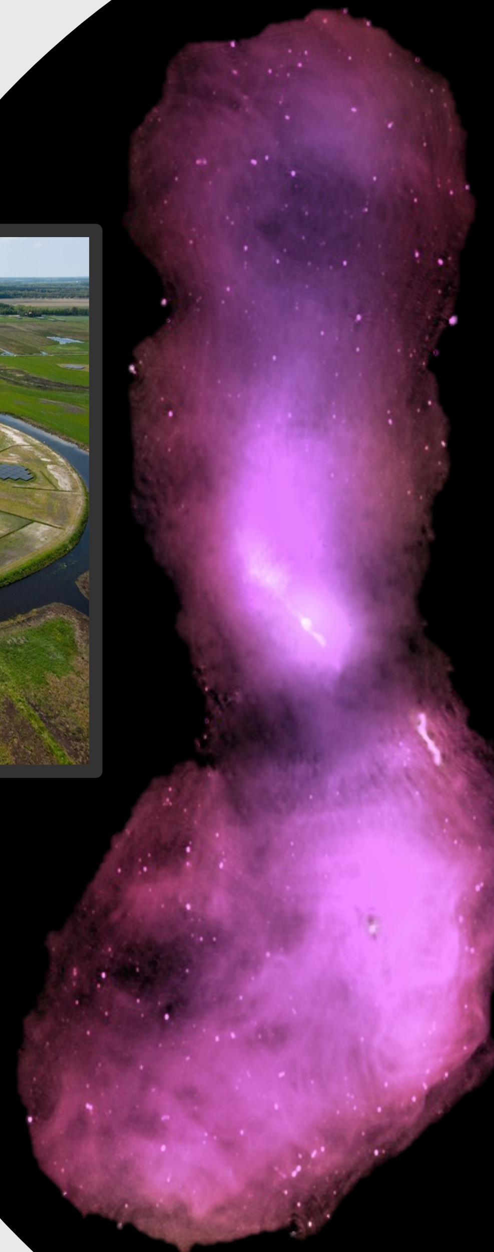
Tailoring Calibration and Imaging aka why the hell are we choosing these values?



Joe Callingham (ASTRON)

Kenyan Radio Astronomy School,
Nairobi, Kenya
30th of May 2018

DARA
DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

UNIVERSITY OF LEEDS

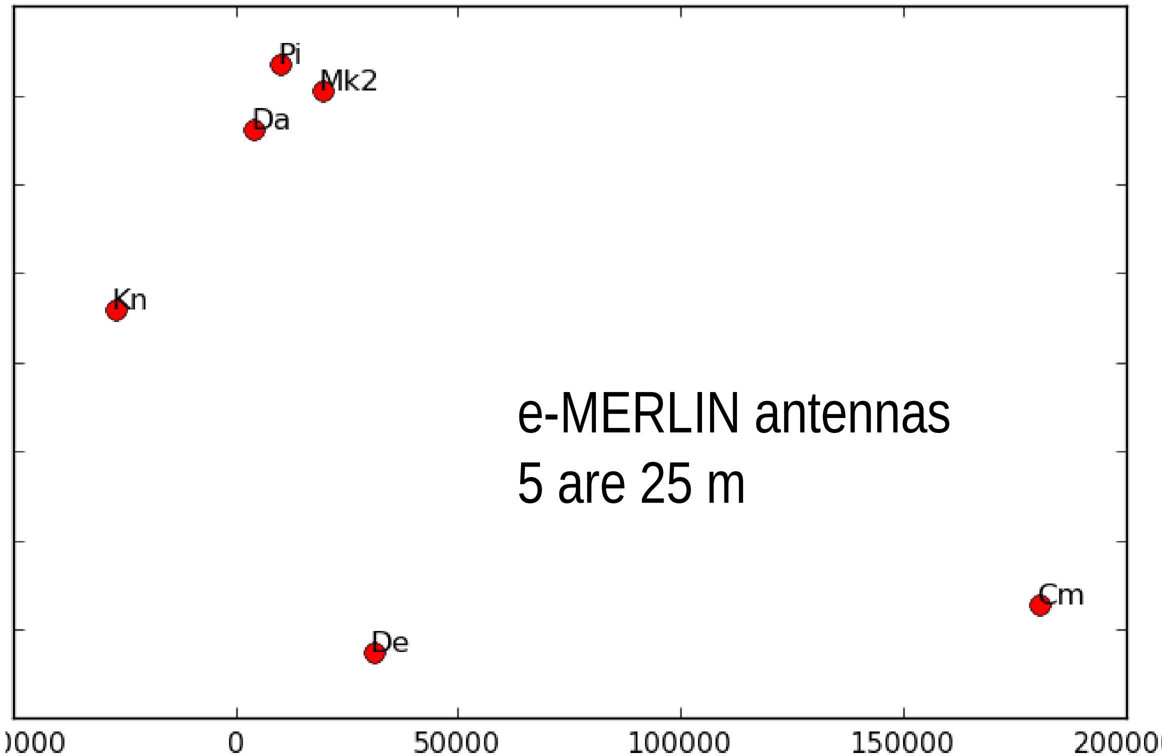
How do we know what parameters to set?

- E.g. what solution interval for phase calibration? Some are standard (just vary due to observing conditions) but others are science goal dependent.
- Are you trying to recover diffuse, faint emission or resolve fine structure?

Choosing reference antenna

- The antenna with the best chance of good solutions to all other antennas
- Most short baselines? Greater atmospheric differences on long baselines
- Most sensitive?

- EVN tend to choose Ef as central and most sensitive
- e-MERLIN: usually use Mk2 (or Pi or Da)

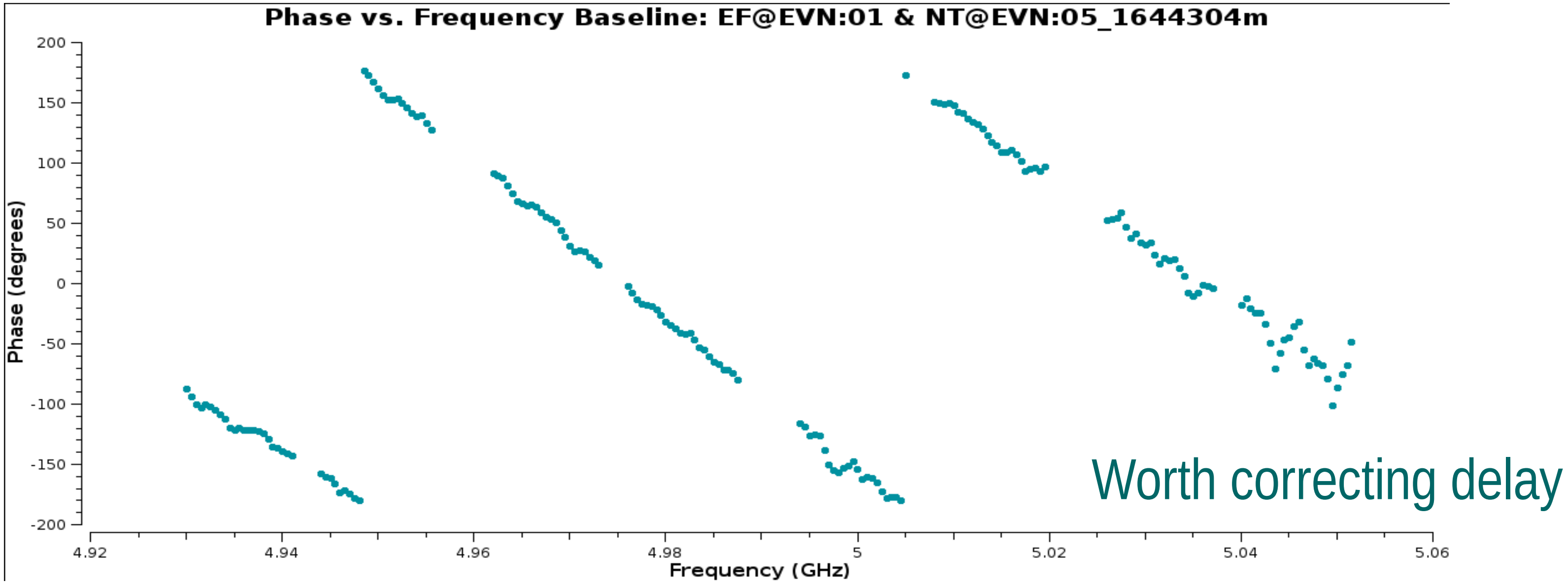


Delay Calibration

› Delay corrections for linear phase gradients: Inspect phase v. frequency

› Only worth correcting delay if you can see it

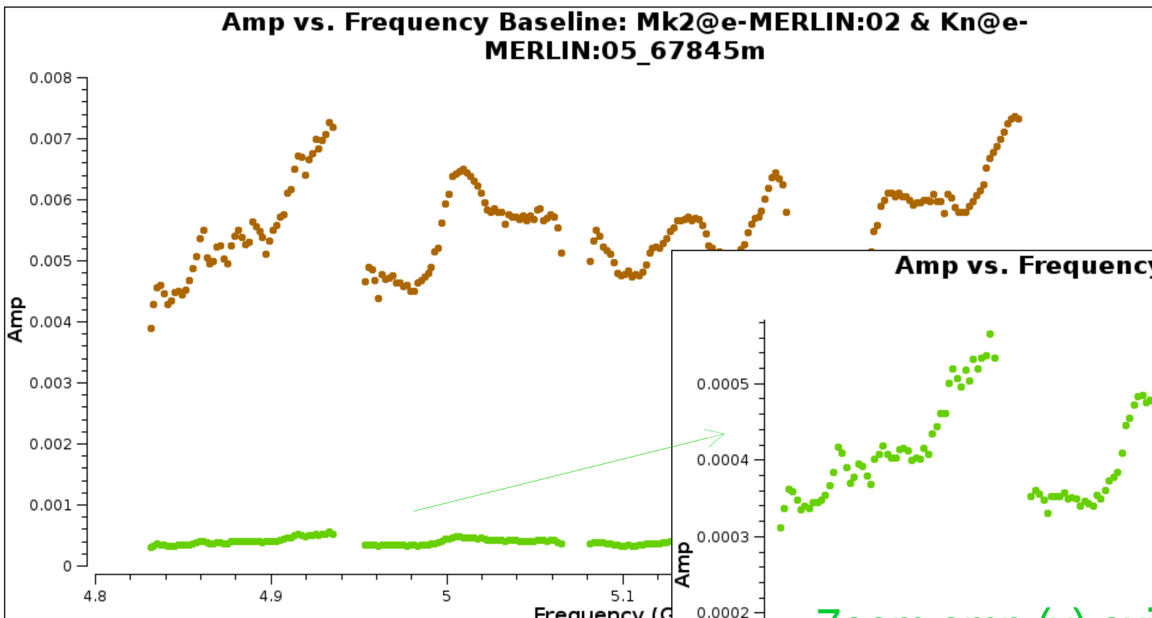
› Usually stable for hours but averaging solint limited (~scan) by time-dependent phase stability

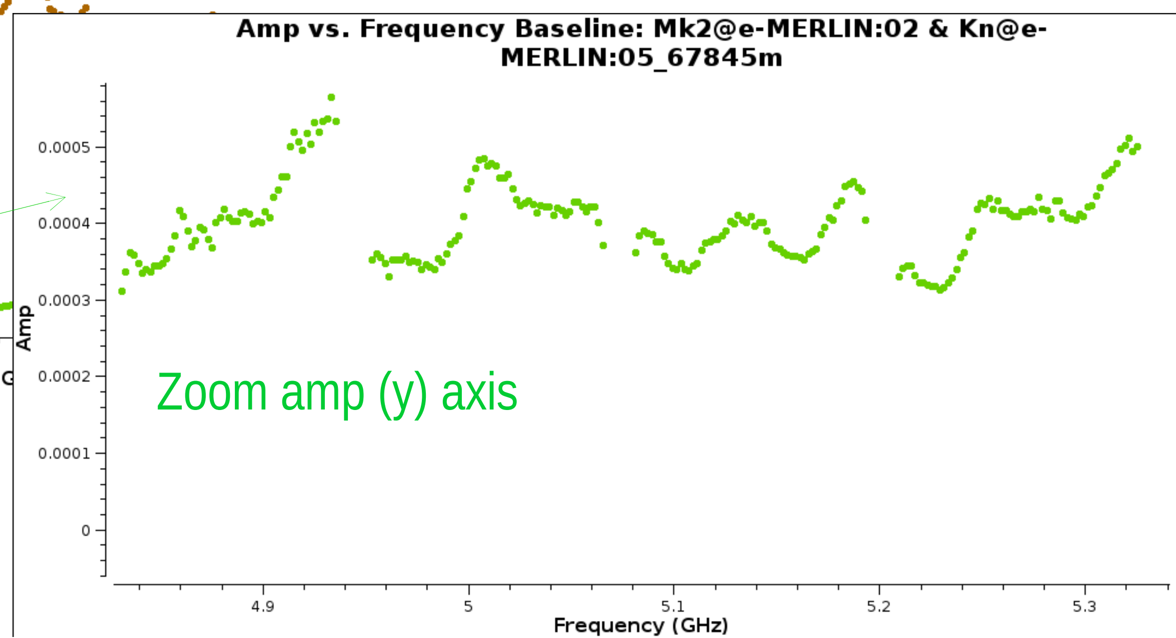


Bandpass calibration

- Correct BP cal phase v. time first (see following slides)
- In Bandpass, average in time for as long as possible for best S/N per channel

- Both BP cals have same amp wiggles
- Could combine, interpolate or use just the one with best S/N





Visibility errors and noise

- Lowest possible noise is 'thermal' limit based on Tsys (assuming natural weighting):

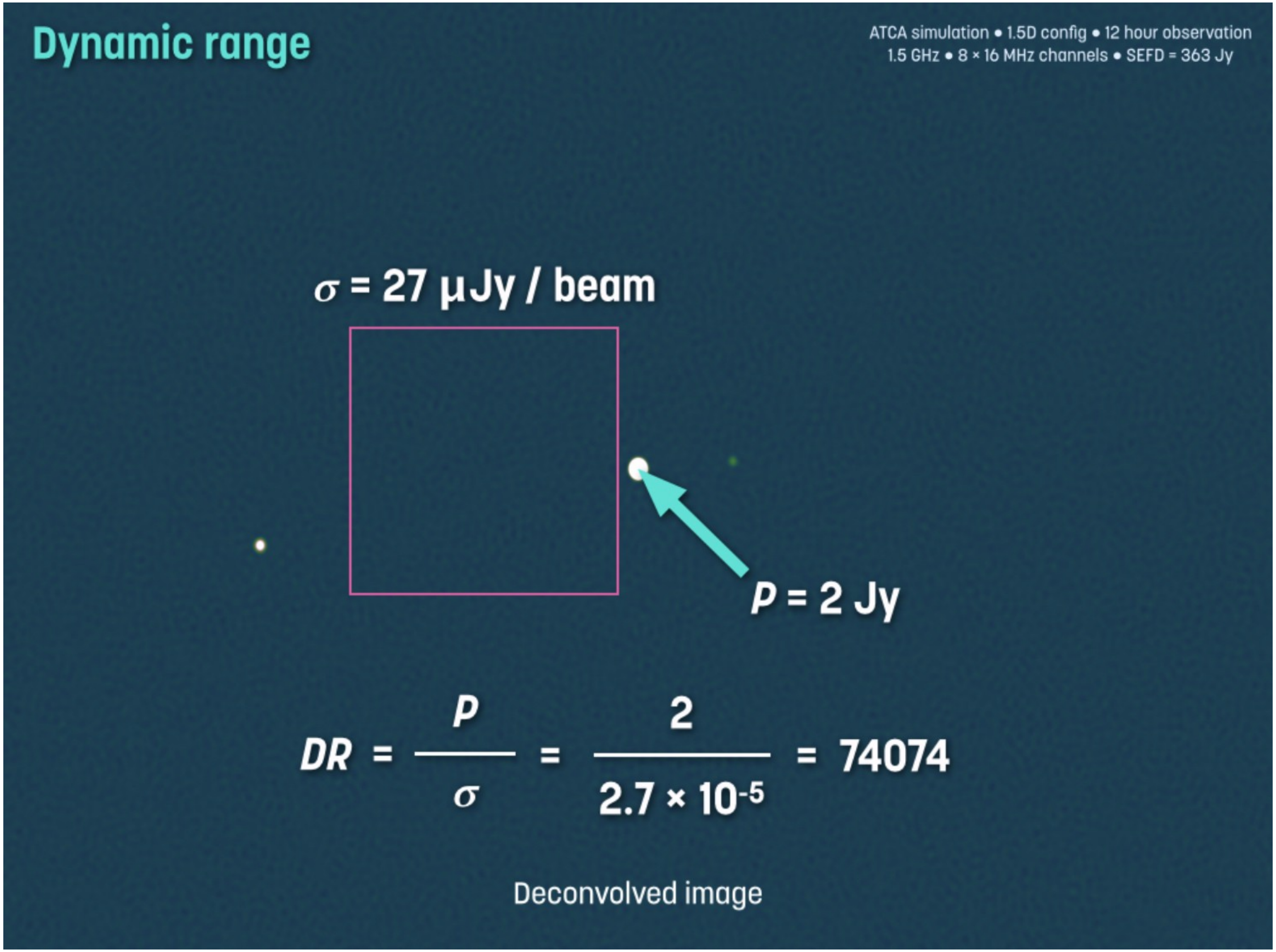
$$\sigma_{sys} = \frac{\langle T_{sys} \rangle}{\eta_A A_{eff} \sqrt{N(N-1)/2 \;\; \Delta\nu \;\; \Delta t \, N_{pol}}}$$

- Good rule of thumb is that you should at least reach 3 times the predicted noise floor (why do you not often reach the noise floor?)

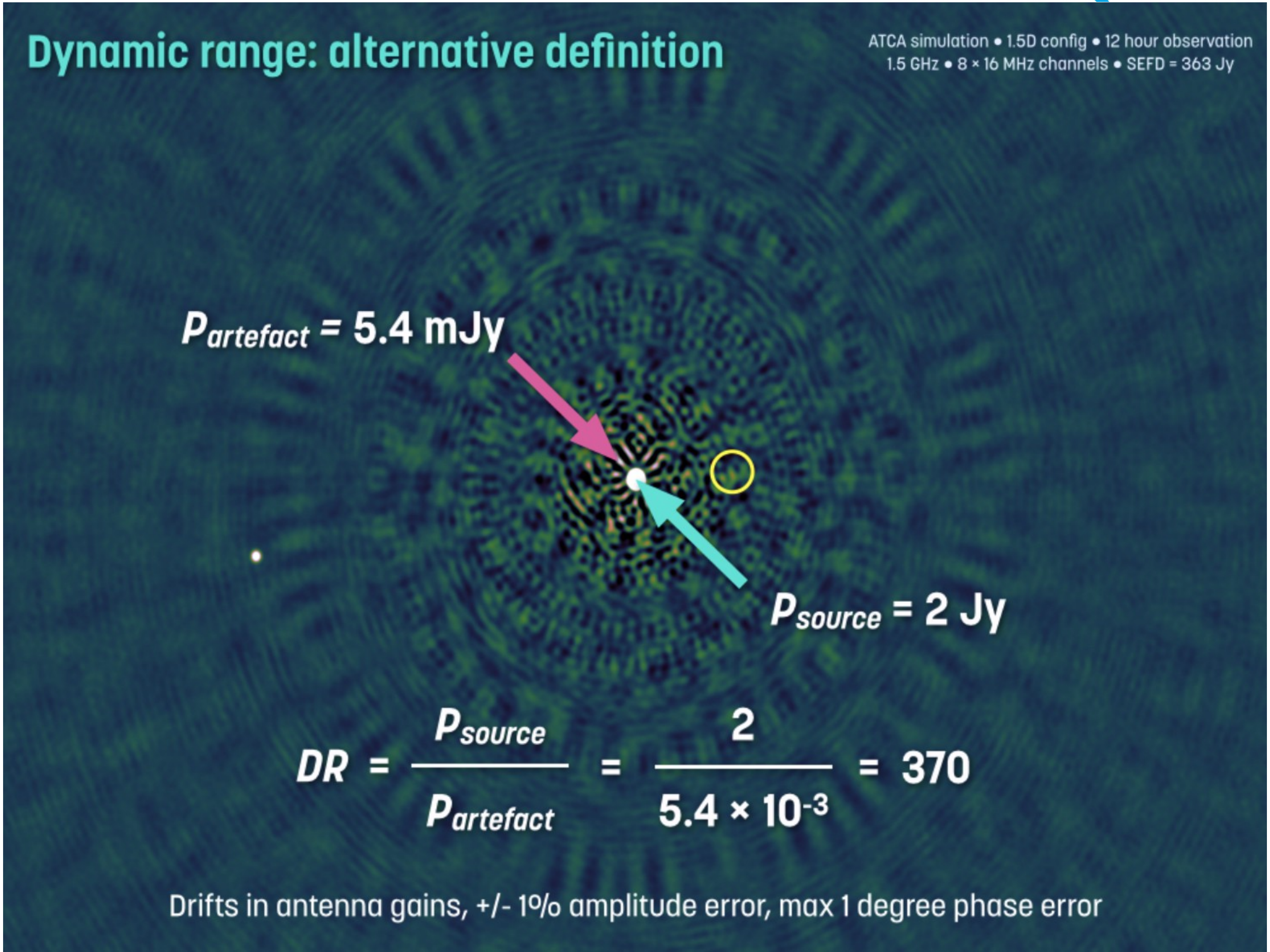
- So you can only improve on this by:
  - Bigger/more efficient antennas (Aeff , hA) or more (N)
  - Lower noise Rx and/or Tsky (observing conditions)
  - Observe for longer/wider bandwidth

Dynamic Range

- What is dynamic range and what counts as high?



Dynamic Range



Phase Errors and Dynamic Range

Image is formed by Fourier transform

- $I(x) = \int V(u)\, e^{i2\pi ux}\, du$
  - Each baseline contributes at position u_k and complex conjugate $-u_k$ in the visibility plane

Evaluating the term in the integral for each of the $[N(N\text{-}1)/2]\text{-}1$ good baselines gives $2\cos(2\pi u_k x)$

Bad baseline gives $2\cos(2\pi u_0 x - \phi_\varepsilon)$

- $\sim 2[\cos(2\pi u_0 x) + \phi_\varepsilon \sin(2\pi u_0 x)]$ for small ϕ_ε (in radians)

- The image integral thus sums to

$$I(x) = 2\varphi_\epsilon \sin(2\pi u_0 x) + 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k x)$$

Phase Errors and Dynamic Range

- The synthesised beam is given by

$$B(x) = 2\sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k x) \quad = N(N\text{-}1) \text{ for } u = 0$$

- Deconvolution is the subtraction of the beam from the image leaving the residual error

$$R(x) = \left[2\varphi_\epsilon \sin(2\pi u_0 x) + 2\sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k x)\right] - 2\sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k x)$$
$$= 2\varphi_\epsilon \sin(2\pi u_0 x)$$

  - an 'odd' sinusoidal function of amplitude $2\phi_\varepsilon$, period $1/u_0$

Calibration errors and dynamic range

- For small phase error ϕ_ε, large N, the ratio of the peak / noise residual is thus
  - Dynamic range $D_B(\phi_\varepsilon) \sim I(x) / R(x) \sim N^2 / \sqrt{2}\,\phi_\varepsilon$
    - e.g., radians (5°)~0.09
- Amplitude error ε on a single baseline has the effect

  $V(u) = (1+\varepsilon)\delta(u - u_0)\, e^{-i\phi}$ leading (via a cos function) to
  - Dynamic range $D_B(\varepsilon) \sim N^2 / \sqrt{2}\,\varepsilon$
- **A phase error of 5° is as bad as a 10% amp error**
- **Phase errors are sin (odd), amp are cos (even)**

Calibration errors and dynamic range

- So far considered one-baseline error, one integration
- All baselines to one antenna affected by same error:
  - (N-1) bad baselines (~N for large N)
  - $\boldsymbol{D}_{\mathbf{ant}} = D_{\mathrm{B}} / (\mathrm{N}-1) = [N^2/(N-1)] / \sqrt{2}\phi_\varepsilon \sim \boldsymbol{N} / \sqrt{\mathbf{2}}\boldsymbol{\phi}_\varepsilon$
- If all baselines are affected by random noise,
  - $\boldsymbol{D}_{\mathbf{all}} = D_{\mathrm{B}} / \sqrt{[N(N-1)/2]} = \sqrt{[N(N-1)/2]}/\phi_\varepsilon \sim \boldsymbol{N}/\boldsymbol{\phi}_\varepsilon$
- These expressions are valid if errors are correlated in time, e.g. single phase-ref scan, not much change in u (or v)
- For M periods (scans?) between which noise is uncorrelated
  - Dynamic range is increased to $\boldsymbol{D}_{\mathbf{all}} \sim \sqrt{\mathbf{M}}\, \boldsymbol{N}/\boldsymbol{\phi}_\varepsilon$

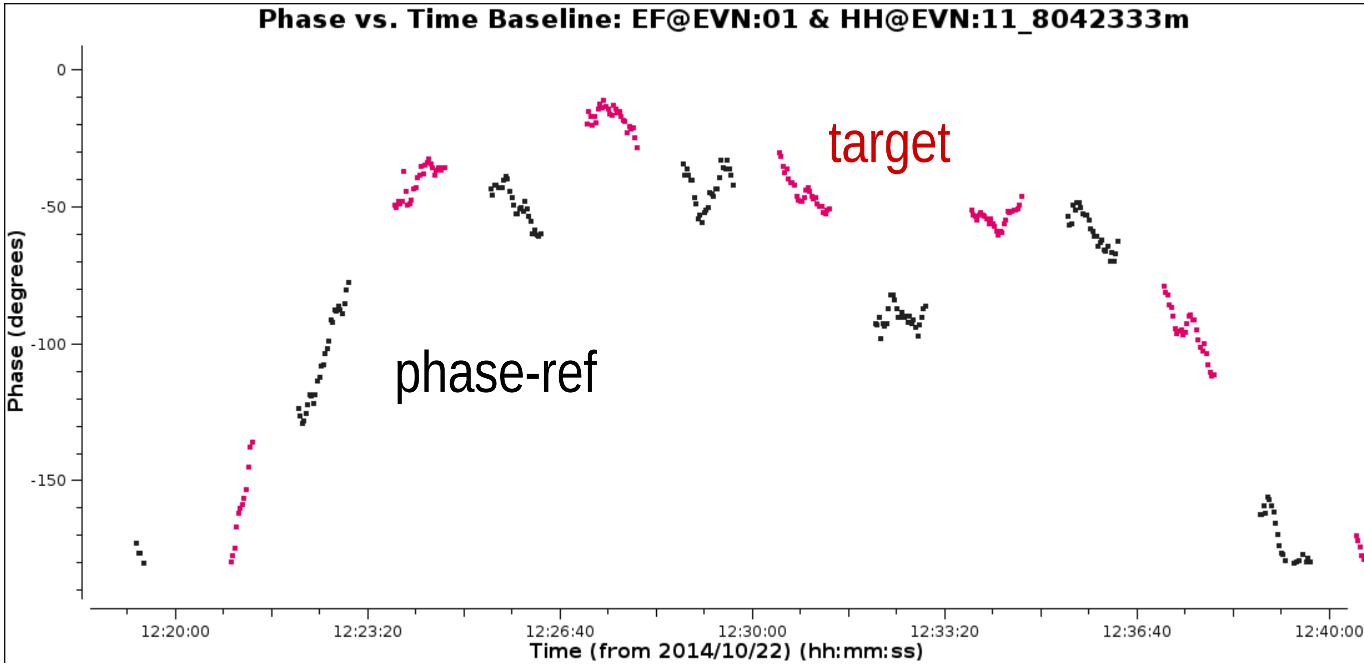
Calibration errors and dynamic range

- Implications so far: take a 10-antenna array
  - Twelve independent scans on a target, phase reference and other calibration applied, well edited
    - Residual phase scatter 20^{o} : $D_{\mathbf{all}} \sim \sqrt{} \; \mathbf{M} \; N/\phi_\varepsilon$
    - ~ 100 dynamic range limit
      - Can you improve by self-calibration?
        - No if map noise have reached the T_{sys} limit and remaining errors are pure noise. If not:
    - Maybe, if some antennas are still imperfectly calibrated
      - Calibrate per antenna, per scan (or longer)
        - Need potential S/N per interval high enough to get ϕ_ε <20^{o}

Time-dependent phase cal

- Apply bandpass/delay corrections
- Phase reference source:
  - Need to interpolate solutions to target
  - Does the phase-ref phase track the target phase?

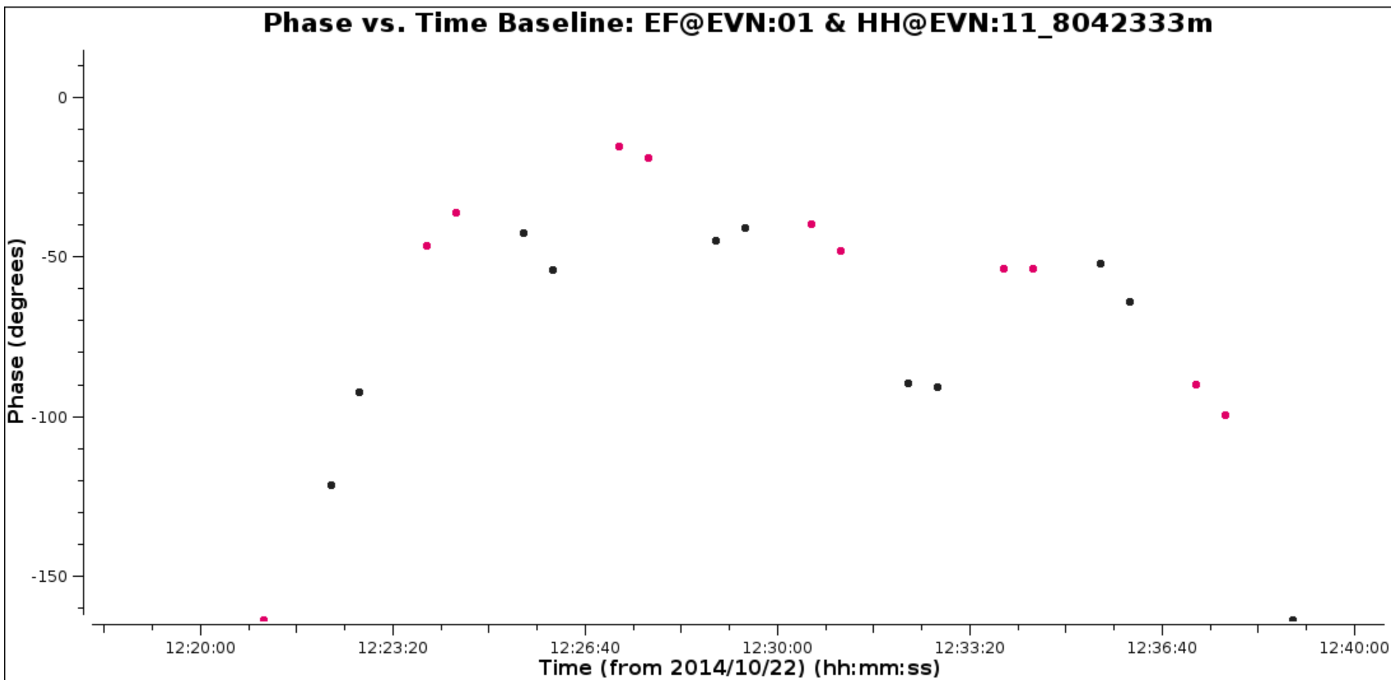
- Consistent trend seen here
  - Target wiggles may be structure
  - Some deviations



Time-dependent phase cal

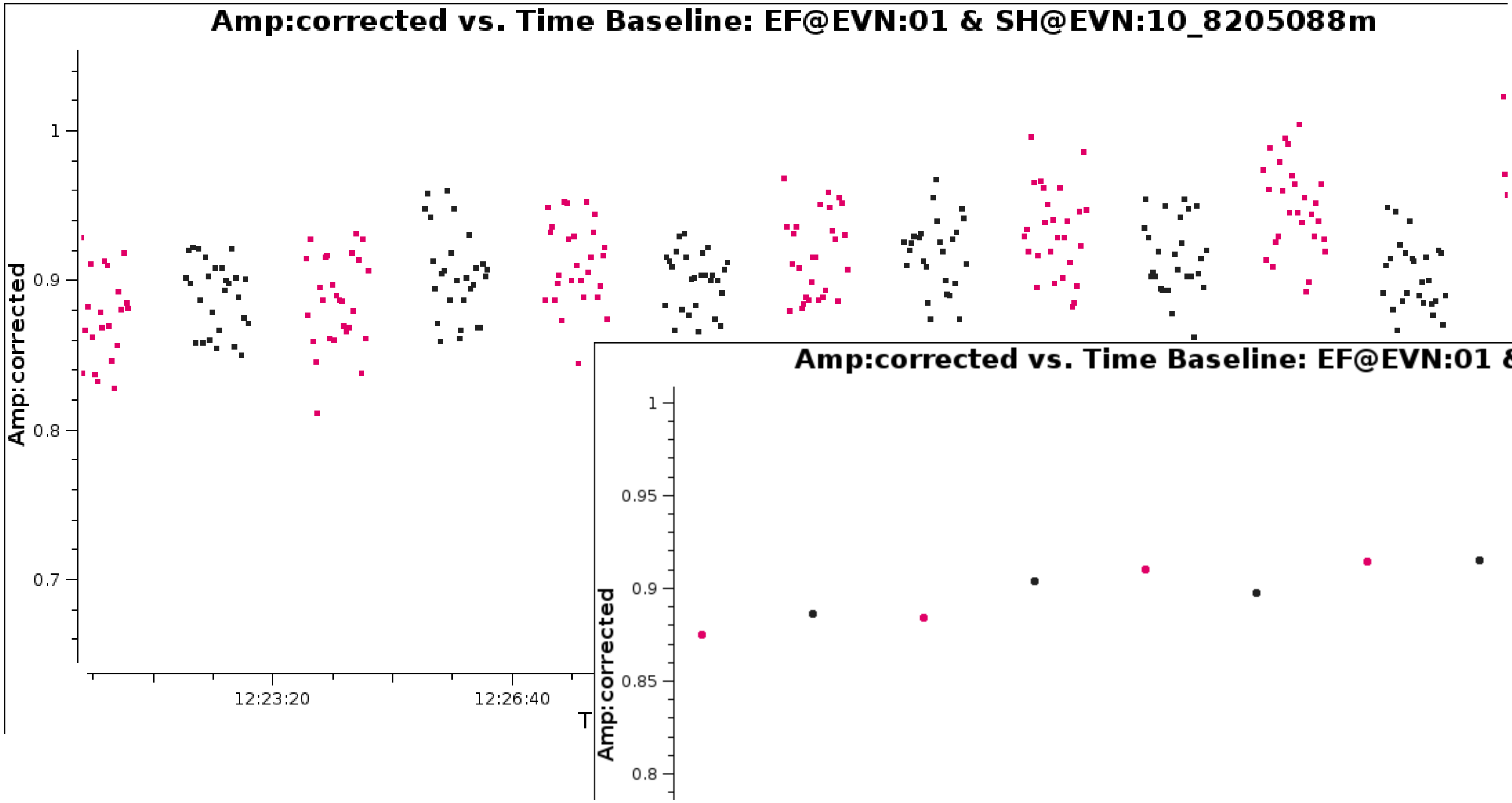
› Need to interpolate phase-ref solutions to target
› Ideally no more than 2 solutions per phase-ref scan
› Check enough S/N in e.g. half scan
› Seeing low scatter by eye is OK!

› Previous plot with 30-s averaging
› 30-s corrections will track phase better than per-scan



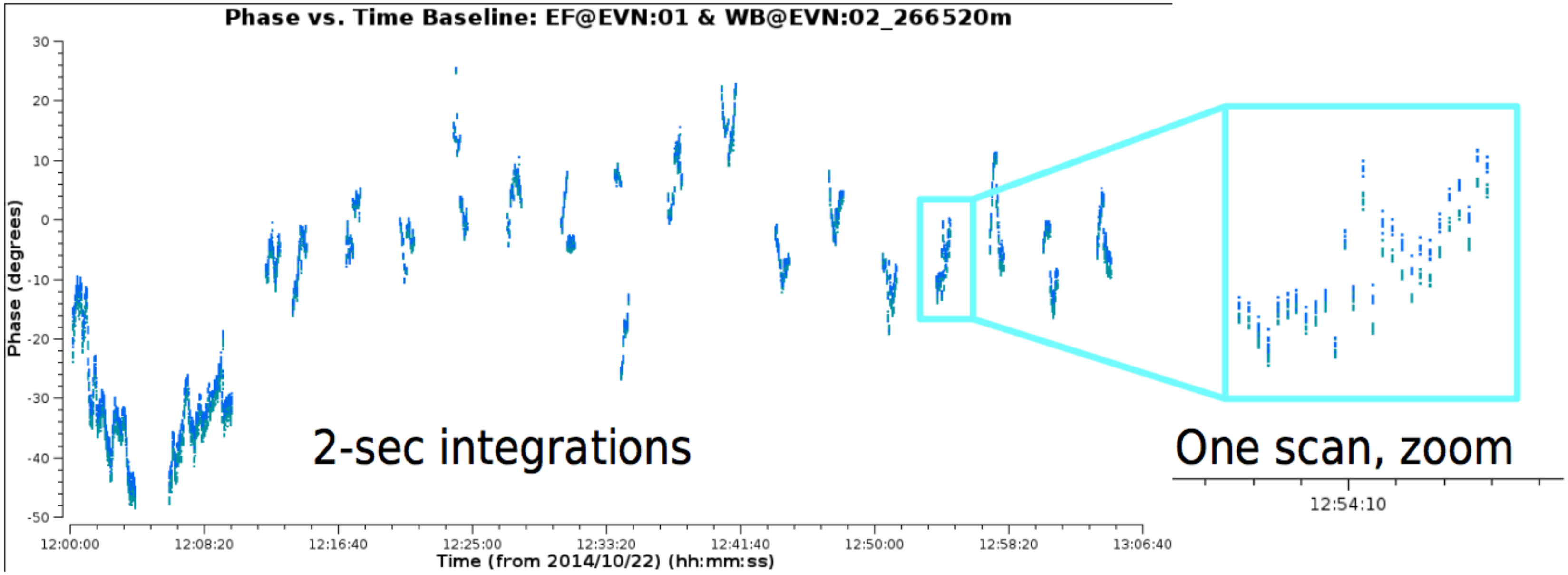
Time-dependent amplitude cal

- Apply phase solutions first to allow longer solint for amplitude calibration
- Avoid decorrelation
- If necessary, use shorter phase-only solint just for this
- Amp scatter per scan usually just noise

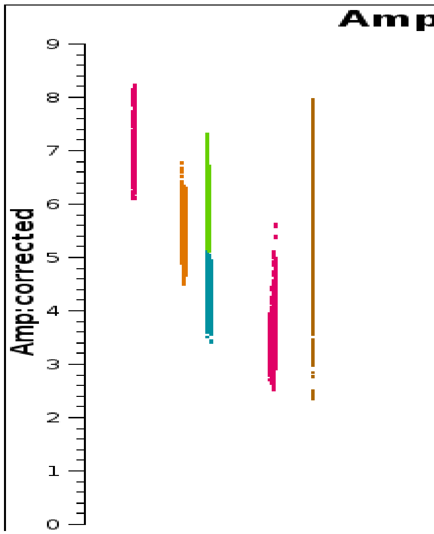


Self-Cal timescales

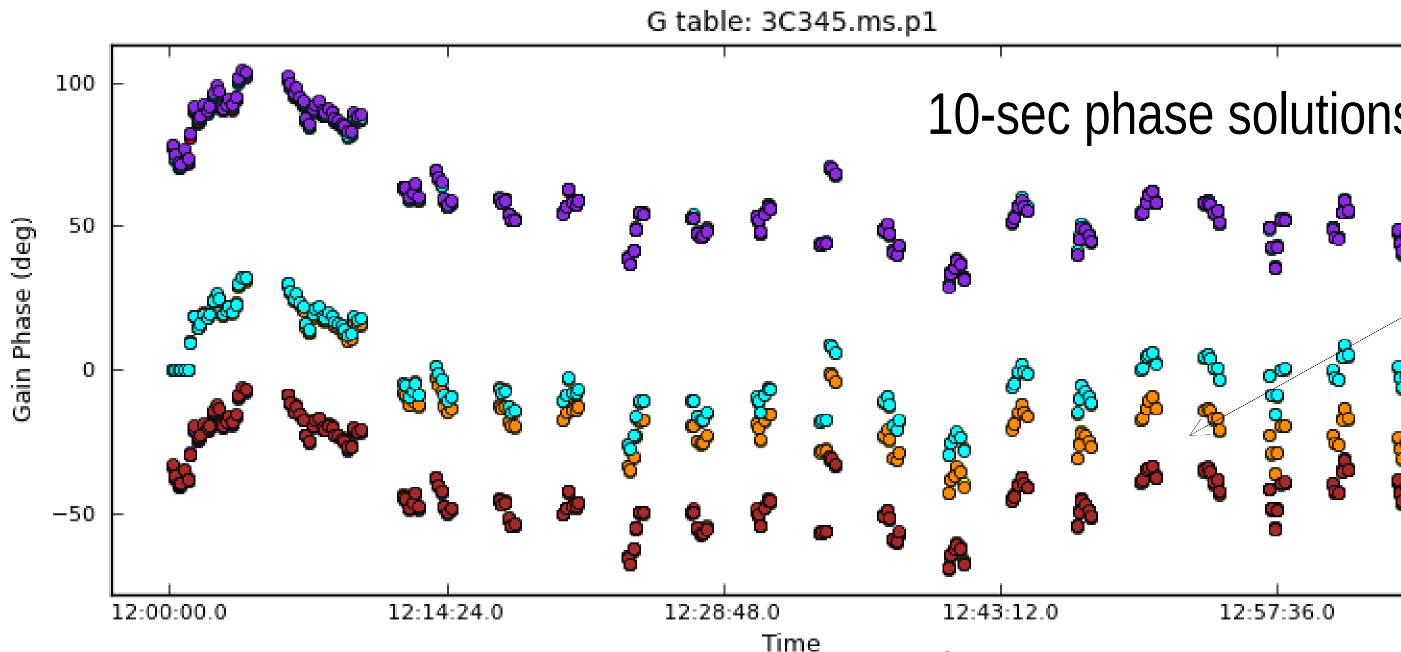
- Target phase (after phs-ref corrections) changes rapidly
  - May be partly source structure, but seen even on short b'lines
    - Not just random noise even on 10-sec timescales



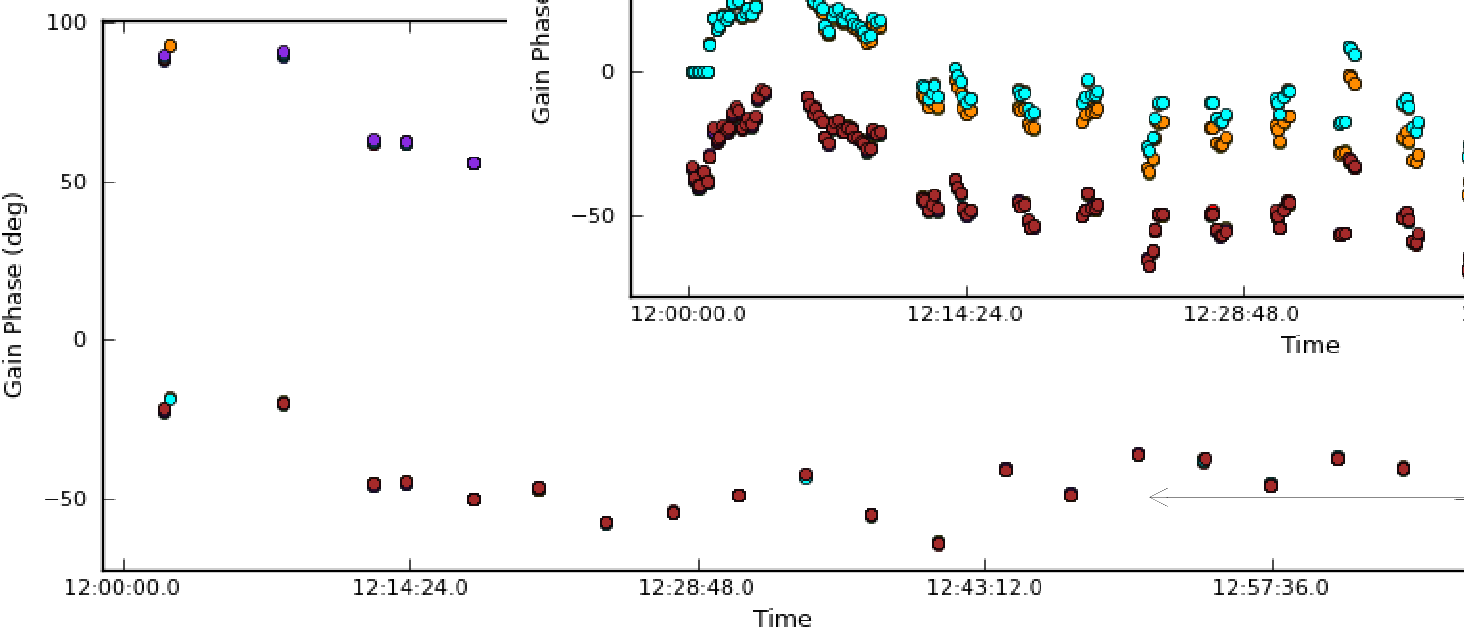
Self-cal timescals



Enough flux on all baselines to refant

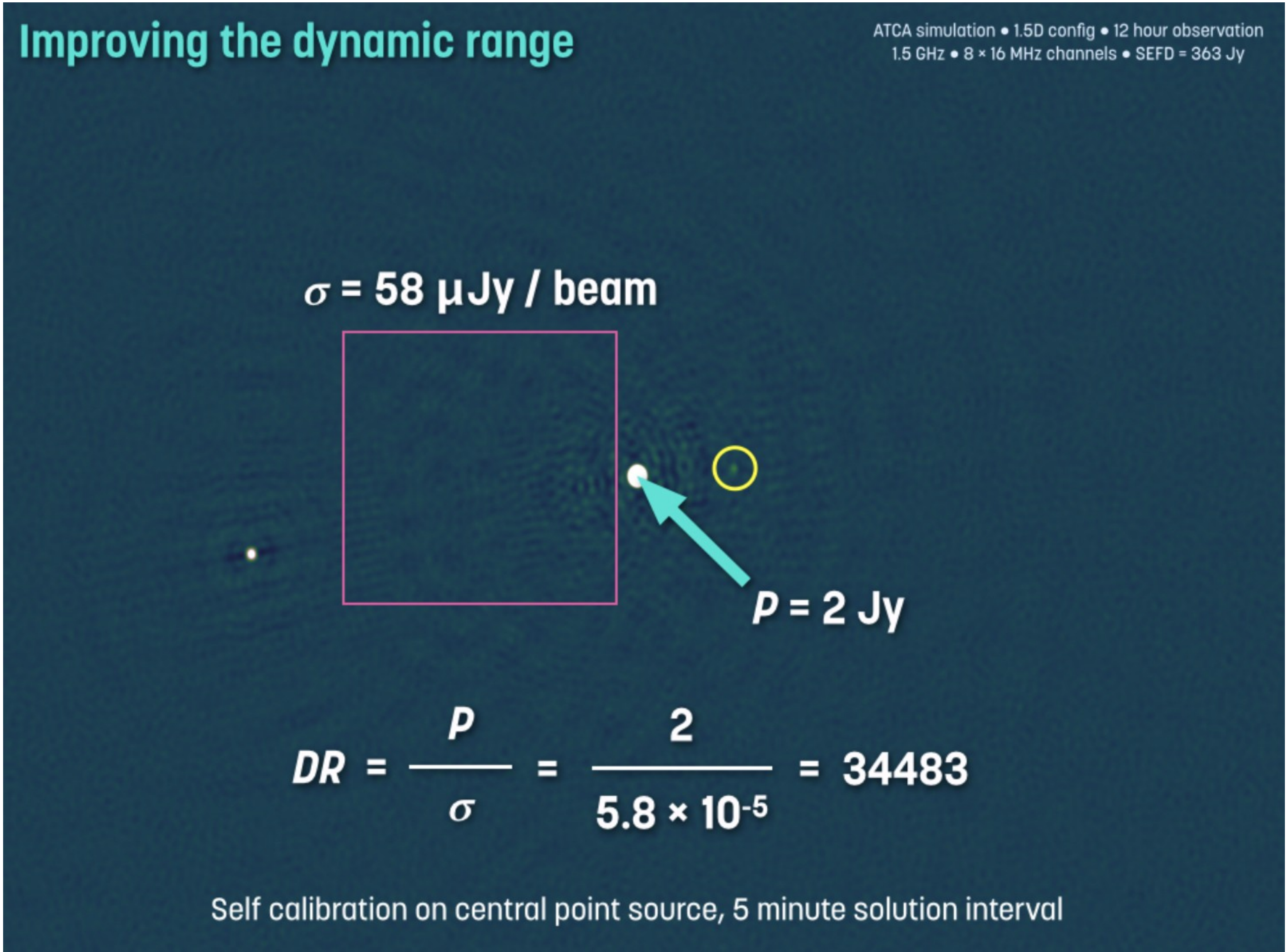


10-sec phase solutions



Track structured phase errors better than per-scan solutions

Self-Cal and dynamic range



Conclusion

- "good" calibration solution depend on the conditions of the observation and science goals
- Identify a good reference antenna
- Bandpass and amplitude solution intervals can be as long as possible to get best S/N
- Best solution interval for phase solutions depend, but almost always shorter than a single scan
- Want the best dynamic range possible
- Self-cal is your friend